Late Quaternary sedimentation and deformation in Santa Monica and Catalina Basins, offshore southern California

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ABSTRACT

The late Pleistocene history of sedimentation in Santa Monica Basin has been documented using seismic-reflection profiles with ground truth provided by drilling at Ocean Drilling Program (ODP) Site 1015 on the basin floor. High-resolution deep-tow boomer profiles together with both multichannel and single-channel seismic-reflection data provide a framework of 15 key horizons in the upper 200 m of basin fill. The uppermost 12 key reflectors, many of which have been traced across much of the basin in the upper 100 m of sediment fill, have been correlated with the sequence cored at ODP Site 1015. Recently completed radiocarbon dating of samples from Site 1015 on the floor of Santa Monica Basin confirmed a Holocene rate of nearly 3 m/ky, which is the highest yet documented for southern California deep-water basins and only slightly lower than the peak rate during sea-level lowstand. The radiocarbon dates provide stratigraphic age control for the upper 12 key reflectors back to 32 ka at ~100 meters below the sea floor (mbsf). The dated stratigraphic sequence is used to evaluate deformation along the linear southwestern margin of Santa Monica Basin that is formed by the Santa Cruz-Catalina Ridge (SC-CR). In the northwestern corner of the basin, turbidite deposits of Hueneme Fan show local evidence for flexure of sediment horizons as young as 6 ka with minor fault offsets as recently as 1.5 ka. Larger scale anticlinal folding (~5 km width and >100 m of relief) of the basin fill is observed for strata older than ~65 ka. Farther south in the basin, however, much of the western as well as the southern margin of Santa Monica Basin shows limited evidence for tectonic activity affecting the basin fill during the last 100 ka.

The Santa Cruz-Catalina Ridge (SC-CR) separates Santa Monica Basin and the Catalina Basin to the west. There is limited seismic-reflection data for study of the sediment fill of Catalina Basin compared to Santa Monica Basin. The effects of sea level on sources for sediment entering the San Gabriel Canyon system on the Long Beach shelf control the largest sediment inputs to Catalina Basin. We use sediment accumulation rates determined from 20 recently obtained piston cores in San Pedro Basin, the Gulf of Santa Catalina, and San Diego Trough as an analog for the rate of sediment input to Catalina Basin. Deformation within the Catalina Basin fill during the latest (<300 ky) Quaternary is recorded by successive tilting and fault offsets of deposits primarily deposited during lowstands of sea level.

INTRODUCTION

The modern basins of the California Continental Borderland (CCB) provide an ideal environment to study tectonic activity along an active transform margin. Rapid deposition, especially in the inner basins adjacent to the continental shelf (e.g., see overviews by Nardin, 1983; Schwalbach and Gorsline, 1985; Shipboard Scientific Party, 1997; Normark et al., 1998), results in expanded sedimentary sections for recording the effects of deformation. The timing of deformation can be determined within several thousand years with chronostratigraphy from dating of sediment cores.

The Santa Monica Basin (Fig. 1) is the focus of this paper because it has the highest rate of sediment accumulation yet established for a Borderland basin. Initial results of drilling at Ocean Drilling Program (ODP) Site 1015 indicated that about 30 m of sediment were deposited during the Holocene (Shipboard Scientific Party, 1997). The sediment accumulation rate is more than four times that suggested from previous studies (e.g., see Nardin, 1983). The Shipboard Scientific Party (1997) suggested that the deepest recovered sediment at 149.5 mbsf (meters below the sea floor) is no older than 60 ka. Santa Monica Basin also encompasses the best set of seismic-reflection profiling data, excluding unpublished, proprietary industry data acquired for petroleum exploration (see tracklines shown in Fig. 1).

The brief review herein is intended to show the progress made to understand late Quaternary sediment accumulation rates for the inner basins of the CCB and to show some examples of how these rates can be used to evaluate deformation with the basin fills. This review is not intended to address regional tectonism. We first establish a high-resolution seismic stratigraphy for late Quaternary deposits of the Santa Monica Basin and to evaluate deformation within its basin-fill sediment. The Catalina Basin to the west of the SC-CR is a closed basin as is Santa Monica Basin and both receive sediment directly from canyon systems on the continental shelf in addition to local sources on the adjacent basin margins. For purposes of this study, Catalina Basin provides a challenge in that there is no drill data available for chronostratigraphic control. The Santa Monica Basin is used as an analog for depositional processes in Catalina Basin and how to evaluate other basins that ultimately receive sediment from submarine canyon systems along the continental shelf of the Borderland. Preliminary results from radiocarbon dating of sediment in other inner basins of the U.S. CCB area as part of a project to evaluate earthquake hazards provide new data on sediment accumulation rates.

Geologic setting

The north end of the study area is bounded by the Santa Monica fault system, which is a zone of faults that extends westward from the Los Angeles River into Santa Monica Bay. It forms the southern edge of the central Transverse Ranges and includes the Anacapa (Dume) and the Malibu coast faults (Fig. 1). The Santa Monica fault system is believed to have become part of a series of north-dipping blind thrusts on which compression similar to that seen in the Transverse Ranges to the north is being expressed beneath the northern Los Angeles basin (Davis et al., 1989).

The Palos Verdes Fault Zone is a major tectonic boundary south and east of the Santa Monica Basin and is believed to be part of a restraining bend that produces local seafloor uplift (Francis et al., 1996). Whether the fault zone extends north of Redondo Canyon is not resolved (e.g., compare Greene and Kennedy, 1986; Sorlien et al., 2003; Broderick et al., 2003 with Fisher et al., 2003). The fault zone passes east of the Palos Verdes Peninsula, beneath San

Pedro Harbor, and into the deep water (Woodring et al., 1946; Fisher et al., 2004a). To the west, the San Pedro Escarpment is succeeded to the northwest by a series of anticlines on the lower basin slope and adjacent basin sediment fill (Fig. 1). The San Pedro Basin fault, which is along or near the contact between basement rocks on the west and the San Pedro Basin sedimentary fill to the east, extends north into the area of the base of slope anticlines in Santa Monica Basin (Fig. 1). Active deformation along the northern and eastern margins of Santa Monica Basin has been the subject of several recent reports, some of which have utilized the early results from dating the sediment at ODP 1015 (Broderick et al., 2003; Fisher et al., 2003; Sorlien et al., 2003).

The western boundary of Santa Monica Basin is the northwest-trending Santa Cruz-Catalina Ridge, which has a steep eastern flank (Fig. 1). The Redondo Knoll closes the southeastern end of the basin. The sediment fill of Santa Monica Basin forms a thick wedge of sediment that exceeds 2.5 km in thickness in the northwestern corner of the basin (Fisher et al., 2003). Two distinct sequences in the basin fill can be delineated: a shallower one that gently slopes toward the southeast (away from the apex of Hueneme Fan) where it onlaps the west-tilted basement block of Redondo Knoll and a deeper one that gently dips to the northwest away from Redondo Knoll.

The Catalina Basin lies west of Santa Catalina Island, which forms a pronounced topographic barrier for sediment coming from the continent (Fig. 1). Basin depth reaches 1200 m southwest of the island, about 300 m deeper than Santa Monica Basin. The Catalina Basin has substantially less sediment fill compared to Santa Monica Basin, having about 800 m over bedrock (see Moore, 1969; Vedder and Howell, 1980; Baher et al., 2004)

Unconformities on the flanks of Catalina Basin demonstrate that adjoining areas were structurally deformed (Jung and Wagner, 1977). Upper Pliocene marine strata now at sea-floor depth of 1250 m near the northwestern end of San Clemente Ridge contain foraminiferal assemblages that imply water depths were nearly twice that deep at the time of deposition. Lower Pliocene beds on Santa Cruz-Catalina Ridge probably were deposited at depths > 2000 m. These depth changes indicate local tectonic uplifts in the central and inner borderland that may have been as much as 2000 m since the early part of the Pliocene epoch and 1000 m since the late part.

Methods

This review of the late Quaternary filling of Santa Monica and Catalina Basins uses a variety of seismic-reflection data types collected over several decades. The most important surveys involved the use of Huntec deep-tow boomer systems together with either single-channel or multichannel seismic-reflection systems using airgun and sleeve-gun sound sources. Unlike conventional 3.5 kHz high-resolution profiling systems that do not effectively image sand-rich deposits, the deep-tow boomer is capable of imaging to 50 m or deeper in sandy turbidite sequences such as those filling Santa Monica Basin (Fig. 2 B; Shipboard Scientific Party (1997) and Piper et al. (1999).

The primary survey for western half of Santa Monica Basin was cruise P-1-92-SC, which was conducted by the Geological Survey of Canada (GSC) in collaboration with the US Geological Survey (USGS). Deep-tow boomer and single-channel seismic-reflection profiles were collected over Hueneme Fan, e.g. the gridded survey west of 119° W. (Fig. 1). The sound source for the seismic-reflection data was a 650-cm^3 sleeve gun, and the signal was recorded using two separate hydrophone arrays at different frequency bands. Details of the cruise operation and equipment used are in Normark et al. (1998) and Piper et al. (1999). The tie between the GSC survey and DOP Site 1015 was accomplished on USGS cruise A-1-98-SC, which collected deep-tow boomer and high-resolution multichannel reflection data using a 575-cm^3 gas-injector (GI) airgun source. The focus of this cruise and later USGS operations was on the inner parts of all Borderland basins as part of offshore earthquake hazard assessments; details of the equipment used are found in cruise reports (Normark et al., 1999a,b). The seaward limit of the USGS operations was generally 35 km (see northeast-southwest trending tracklines in Figure 1), so older seismic-reflection data collected with a sparker sound source was used to look at that part of the basin margin west of Redondo Knoll, e.g., Fig. 2C.

Data from Catalina Basin are from USGS cruise L-4-90-SC and the collaborative LARSE experiment in 1994 that was conducted on the R/V Ewing (E-15-94-SC). Details for equipment and operations for these cruises can be found in Bohannon and Geist (1998) and Brocher et al. (1995), respectively. Both cruises used large airgun arrays for sound sources and, as a result, the multichannel profiles are not well suited for defining the seismic-stratigraphy of the upper part of sediment fill in basins. To utilize the data for this study, we selected one channel of the LARSE multichannel data and attempted to utilize its highest frequency content. For the L-4-90-SC cruise, we interpreted single-channel records obtained using a high-resolution streamer used concurrently (with the multichannel source) filtering the signal to 40 to 200 Hz.

Complete position data (navigation files) and metadata for all cruises used as data sources in this report can be accessed at: http://walrus.wr.usgs.gov/infobank/.

RESULTS

Seismic-stratigraphic age control

Normark et al. (1998) and Piper et al. (1999) developed a seismic-stratigraphic framework for Hueneme Fan in Santa Monica Basin and identified 15 key reflectors, many of which they traced across much of the basin. These key reflectors are denoted in alphabetical order from the deepest (A) to the shallowest (O). The uppermost reflectors (J to O) are best mapped using the Huntec deep-tow boomer system (Fig. 2B). ODP Site 1015 was placed near the middle of the basin plain area in Santa Monica Basin and was several kilometers away from GSC survey tracks. The subsequent USGS cruise in 1998 placed three lines across the Site 1015 to provide direct ties to two places along the eastern margin of Santa Monica Basin and to provide a tie to the earlier GSC survey (Figs. 1 and 2). The key reflectors from J and deeper can be recognized in both single-channel and multichannel profiles; the example in Figure 2C is illustrated because it is parallel to, and nearly coincident with, the deep-tow boomer profile in Figure 2B. A few of the key reflectors recognized on Hueneme Fan become less distinct on the distal basin plain in the area around Site 1015 and have not been included in Figure 2.

The sediment log for Site 1015 is based on the visual core descriptions (vcds) done by the Shipboard Scientific Party (1997) that we obtained from ODP. Two holes (1015 A and B) were cored and the log shown in Figure 2A is a composite combining descriptions from both holes to obtain a continuous section. The log shown in Figure 2A is simplified from Piper et al. (2003). Because of the high sand content of the cores from Site 1015, the cores were not considered useful for paleoclimatic work, which was the focus of ODP Leg 167. As a result, Site 1015 was basically ignored during later work by the scientists who participated on Leg 167. Normark and McGann (2004) undertook a sampling program to provide age control for the key reflector stratigraphy. Hemipelagic mud intervals were sampled to obtain foraminifera for AMS radiocarbon dating; arrows along the left side of the sediment log in Figure 2A show the dated intervals; the ages were then assigned to most of the key reflectors as shown to the far left of the sediment log. The sediment accumulation rates are shown in Figure 2D.

Although Site 1015A extends to 149.5 mbsf, several attempts to find datable carbonate below 100 mbsf were unsuccessful. As a result, there is no direct age control for reflector C, which is about 140 mbsf. For this study, the ages of key reflectors A to C have been estimated by extrapolation of the sediment accumulation rates based on the lowermost three radiocarbon ages shown in Figure 2. The extrapolation suggests that C could be as young as 55 ka, and this is consistent with the Shipboard Scientific Party (1997) estimate that the bottom of Site 1015A is < 60 ka. The deepest reflector (A) is about 75 ka based on age extrapolation, but it could be older if sediment accumulation varied substantially before 60 ka. In any case, we believe that reflector A is younger than 100 ka because available seismic-reflection data from Hueneme Fan shows no evidence for a hiatus in deposition between the bottom of ODP 1015A and reflector A. To be older than 100 ka, the sediment accumulation rate would have to have been as low as during the brief period of rapid rise of sea level during the Holocene (Fig. 2D).

Western Margin of Santa Monica Basin

The sediment fill in northwest corner of Santa Monica Basin is cut by a set of short unnamed faults that were previously recognized and shown in the Greene and Kennedy (1986) compilation (see Fig. 1). We can now assess the timing of deformation using the improved age control from ODP 1015. The northernmost structure is shown in Figure 3 where a GSC sleeve-gun profile crosses an anticlinal structure that is about 5 km across and with 100 m of relief. The oldest horizon (A) is near the top of the sequence involved in the folding, but reflectors B through F onlap the north flank of the fold with little evidence for continuing growth of the anticline. By about 20 ka (reflector F), it appears that turbidity currents from Hueneme fan are able to overtop the crest of the anticline and deposit sediment near the base of the slope to the southwest. Turbidity currents from Hueneme Canyon deposit along lower basin slopes more than 40 m above the adjacent basin floor (Piper et al., 2003); thus the currents could easily overtop the anticline crest in this proximal fan setting. Minor faulting within the axial zone of the anticline does not extend far into the sediment overlying the fold. Thus, the structure and associated faults appear to have formed prior to 65 ka (Fig. 2A), but the modern sea floor is slightly upbowed over the crest of the anticline, suggesting that uplift with little folding may be continuing slowly.

Closer to the basin margin, minor faulting has disrupted beds younger than 60 ka, but older than 13 ka when key reflector J was deposited (Fig. 4). In this profile, which was obtained with the NSRF receiver and sleeve-gun source, the relatively acoustically transparent character of the interval immediately below J precluded a more precise determination of the latest deformation.

Along the base of the SC-CR, the southernmost structure shown in the maps of Greene and Kennedy (1986) in the western corner of Santa Monica Basin is associated with minor folding (Fig. 5) of the youngest fan deposits. A hinge line clearly observed below key reflector O (1.5 ka; see Fig. 2A) developed above a fault observed the NSRF profile along this line. Most offset on the fault occurs below about reflector F (20 ka). A small graben-like feature appears to post-date the flexure apparently truncating beds as young as 1.5 ka (O) as seen in Fig 5A. In Figure 5B, however, deposition younger than N appears to onlap the dipping beds involved in the flexure. The graben-like feature does not appear to be a segment of a channel along the base of the slope because there is no evidence in other profiles that shows a continuation of this feature along the slope.

Along the base of the SC-CR 25 km to the southeast, there is limited evidence for deformation within the sediment fill of Santa Monica Basin younger than about C (60 ka). Figure 6A is a sleeve-gun profile that shows basin-floor sediment onlapping the base of the SC-CR for reflectors as deep as A. Three to four kilometers northeast of the ridge, there is a slight deepening of the reflectors toward the basin axis that might be related to transtension in the more distal Hueneme Fan area. The high-resolution deep-tow boomer profile (Fig. 6B) shows onlap of turbidites at the base of the SC-CR with the sediment layers apparently slightly uptilted. This geometry could reflect tectonic uplift of the ridge or slightly increased deposition from southward flowing turbidity currents that are forced toward the base of the ridge as a result of the Coriolis force. The possibility of deposition from turbidity current flow is further demonstrated by the small leveed channel that has evolved in the base of slope area during the last 1.5 ka (post O).

About 15 km farther southeast along the base of the SC-CR, onlap of tabular bedding of the basin plain area characterizes all units from C (60 ka) to the sea floor (Fig. 7). Reflector C onlaps a gentle upwarp toward the base of the ridge, but only below A is there evidence for folding of sediment near the base on the SC-CR. The profile continues upslope onto the SC-CR, and there is probably a fault zone along the depression that is about three kilometers from the basin floor. Greene and Kennedy (1986) show a fault long this re-entrant on the flank of the SC-CR (shown in Fig. 1), but our study provides no age control for the activity of a fault along this trend.

The sparker profile that passes ODP Site 1015 (Fig. 2C) onlaps the southern margin of the basin showing no evidence for deformation younger than C. Deeper reflectors show evidence for acoustic artifacts that probably result from methane hydrates in the sediment (e.g., see

Normark et al., 2003). In general, evidence for latest Quaternary deformation of basin-fill sediment adjacent to the southwestern margin of the Santa Monica Basin is less than for the northern and eastern margin (Fisher et al., 2003; Broderick et al., 2003; Bohannon et al., 2004).

Catalina Basin

Catalina Basin was known to have turbidite fill as a result of early sampling and seismic-reflection studies (e.g., Gorsline and Emery, 1959; Emery, 1960; Moore, 1969). Although Catalina Basin is not an inner basin of the Borderland, it is directly fed by a canyon system on the San Pedro shelf (Fig. 8). The San Gabriel Canyon feeds a turbidite channel that crosses the Palos Verdes fault zone at the northwest corner of Lasuen Knoll (Figs. 1 and 8). The channel bifurcates immediately downslope from its crossing the fault zone, and detailed multibeam imagery shows that a submarine slide is at least partially blocking the eastern branch, which hugs the west side of Lasuen Knoll for a short distance (inset image, Fig. 8). Both branches of the channel have high western levees, and both appear to have undergone erosional deepening (Fig. 8D).

The western branch of the channel has a sinuous form as it traverses the basin toward the south end of the Catalina Ridge. The eastern branch appears to end in a low relief depositional lobe (Fig. 8C). South of Avalon Knoll, the western branch with broad terraces appears to be tilted in cross section over a basement high associated with the San Pedro Basin fault zone (Fig. 8B). The erosional nature of the channel continues until reaching the sill with Catalina Basin (Fig. 8C and inset). Thus, the San Gabriel channel is a bypass zone feeding sediment to Catalina Basin.

Unlike Hueneme Fan, most modern submarine turbidite systems show markedly reduced sediment accumulation rates as sea level rose during the Holocene (see reviews in Bouma et al., 1985). Preliminary results of our current study suggest that for non-delta-fed systems in the CCB, late Pleistocene sediment accumulation rates are from two to ten times the Holocene rate. These rates are based on the initial phase of radiocarbon dating of more than 40 piston cores from the inner basins of the CCB. The Holocene deposits are generally finer grained with fewer sand and silt beds as there is a marked decrease in coarse sediment input during sea-level rise. Catalina Basin shows a similar trend with a shift to mud deposition during the Holocene (Brandsma et al., 1989).

The Santa Monica Basin, which is closed, shows a late Holocene sediment accumulation rate that is close to the rate during the maximum lowstand (Fig. 2D). This smaller difference in rates between Holocene and late Pleistocene reflects the active deltaic source for the Santa Monica Basin where the Santa Clara River delta was able to prograde back to the shelf edge (Piper et al., 2003). The Huntec data from the San Gabriel channels shows that before the eastern channel was blocked, its levee prograded over the low-relief levee of the western branch (Fig. 8D). The uppermost unit is an acoustically transparent layer that is clearly recognizable except over the floor of the western channel. The transparent layer was cored (arrow at left side of Fig. 8A) and the base of the Holocene is ~1.8 mbsf, which corresponds to the base of the transparent layer (dates from M. McGann, written comm., 2004). This layer is dominantly mud, suggesting that it is probably the result of mostly hemipelagic deposition during the Holocene. A muddy sequence of Holocene age of about the same thickness has been described for Catalina Basin (Brandsma et al., 1989).

During the late Pleistocene, sediment accumulation rates for most inner basins of the CCB were substantially higher. For example, our new dates show that the Holocene rate of muddy sediment deposition in San Diego Trough is about 15 cm/ky. The deep coring on the fan as part of the Mohole project, however, showed a late Pleistocene rate of more than 200 cm/ky (Inman and Goldberg, 1963). Dating of our recently obtained cores also shows increased late Pleistocene sediment accumulation rates at sites where the cores are long enough to penetrate enough of the Pleistocene deposits. The higher rates during the late Pleistocene result from lowered sea level when the submarine canyon heads are close to the beach. For this reason, the San Gabriel Canyon could receive more sediment during lowstand, and as a result, a lot of coarse sediment entering the canyon bypassed to Catalina Basin.

It is less straightforward to decipher the sedimentation record in Catalina Basin than for Santa Monica Basin. Seismic-reflection profiles available for Catalina Basin are few in number and are low frequency multichannel records that do not have the resolution of sedimentary units as recorded in the high-resolution multichannel data from the 1998 and 1999 USGS cruises (compare profile of Fig. 8B to those of 8A and 8C). There is no deep-tow boomer data available from the basin, but 3.5-kHz profiles confirm that the near surface sediments are relatively coarse-grained based on the lack of resolution of deeper (i.e., >5 m) reflectors. Both the 3.5-kHz and airgun seismic-reflection profiles show some channel features as well as local seafloor relief that is indicative of a channel-lobe transition zone (Mutti and Normark, 1991; Piper et al., 1999). Thus, available data are consistent with the conclusion that the Catalina Basin fill results from a series of discrete turbidite sequences whose deposition is separated in time sufficiently to record deformation between the sequences. Erosion of emergent islands and banks is increased during low stands of sea level, but the seismic-reflection data does not implicate any major local sources.

Figure 9 shows reflection profiles that cross the middle and southern part of Catalina Basin. Several seismic-stratigraphic units with the acoustic character of turbidite deposits that exhibit subtle relief of their bounding surfaces are identified. In general, the basin floor is rather flat as the result of deposition on a slightly undulating surface, which is marked in blue. This upper ponded unit rests on a sequence (between blue and red surfaces) that onlaps the western flank of Catalina Island and smoothed the pre-existing relief. Turbidite channels are seen both on the present sea floor and on the blue surface. In turn, the unit below the red interface onlaps both basin margins shows a higher relief of the assumed turbidite reflectors These three units (and probably at least one deeper unit) are part of the turbidite fill of Catalina Basin identified by Moore (1969) as post-orogenic. Profile in Figure 9D shows the correlation between 9B and 9C. The uppermost stratigraphic unit (blue to the seafloor) is probably the result of deposition during the last sea-level lowstand (OIS 2) corresponding to the sequence deposited in the overbank area of the eastern channel from San Gabriel Canyon (Fig. 8A and D).

The earlier turbidite sequence (between red and blue surfaces) appears to be slightly uplifted over the basement high seen in Figure 9A and B and along the western side of the basin where the San Clemente Fault zone bounds the ridge. This sequence is thicker than the OIS-2 interval and onlaps the Catalina Escarpment in all the profiles (Fig. 9). Much of this thicker turbidite sequence may have been deposited during OIS 6 when sea level was at least as low as during OIS 2 for a longer period (see review in Skene et al., 1998). The sequence below red shows more deformation, especially uplift along both the Santa Catalina Escarpment and San Clemente Ridge. If the interpretation of timing of deposition for the younger sequences given above is correct, the sequence below red might have been deposited primarily during the previous sea-level lowstand during OIS 8.

Despite the uncertainties in timing of basin deformation because of the lack of age data for the seismic-stratigraphic sequences in Catalina Basin, the general conclusion is that the basin is continuing to be deformed during the latest Quaternary. Transpression along the San Clemente Fault Zone and the Santa Cruz-Catalina Ridge is gradually shortening the basin along a northeast-southwest axis. Work to date suggests that motion along the San Clemente Fault Zone is probably the main cause of the shortening (Legg, 1991; Legg et al., 2004). Legg et al. (1998) show that along the northern segment of the fault zone, a graben has developed (e.g., Fig. 9A, west side of profile) indicating transtension locally.

San Pedro Basin

Catalina Island is bordered to the east by both the San Pedro Basin and the basinal area between Avalon and Crespi Knolls (Figs. 1 and 8). The San Pedro Shelf and slope consists of highly folded and faulted sediments with a thickness increasing from the top of the shelf from 0.3 to 0.5 km within San Pedro Basin. Several recent papers have extensively discussed the complex structure under the slope and basin areas between the San Pedro Shelf and Avalon Knoll (Fisher et al., 2004b; Bohannon et al., 2004; Baher et al., 2004). Our attempts to evaluate the timing of deformation have not been successful to date. The sediment filling San Pedro Basin is predominantly sand similar to Santa Monica Basin (Haner, 1971), but there has been no scientific drilling in San Pedro Basin. Attempts to correlate the chronostratigraphy from Santa Monica Basin with deposits in San Pedro Basin are thwarted by the relief of the Redondo Knoll, which separates the two basins. Piston cores from San Pedro Basin taken for the current earthquake hazard study have recovered only near-surface sandy sediment (that stops the corer) younger than 1000 yr. The Palos Verdes debris avalanche at the base of the San Pedro Escarpment (Fig. 1) has been dated at ~7.5 ka (Normark et al., 2003) based on dated piston cores from the margin of the avalanche.

DISCUSSION AND FUTURE WORK

The timing of deformation during the late Quaternary within Santa Monica Basin can be determined to within about 1000 y or less (Fig. 2D). This is possible because the primary source of sediment moving to the basin, which is from the Santa Clara River delta, remains active even during the present highstand of sea level. The Hueneme Fan is directly fed by canyons on the delta slope. During the last glacial maximum, sediment accumulation rate was as great as 4 m/ky (Piper et al., 2003). The rate decreased during the early Holocene as sea level rose, but after sea level reached its present position, the delta was able to prograde back to the shelf edge and the accumulation rate for the last few thousand years is about 3 m/ky. Turbidity currents generated at the delta appear to occur about every 250 y, e.g., Fig. 2 shows more than 40 turbidite silt/sand beds during the last 11 ka..

In contrast, the San Gabriel Canyon is now receiving less sediment (than Hueneme Canyon) during the Holocene highstand of sea level because there is no active delta front at the shelf edge. The canyon head presently lies far offshore (Fig. 8 inset). The lack of depositional activity during the Holocene is shown by the transparent muddy sediment layer that covers all but the channel floor (Fig. 8D). Although the San Gabriel canyon system is probably not shut off completely, much less material is available to move through the channel into Catalina Basin. Deformation in Catalina Basin can be documented only over a longer time scale (~10 to 50 ka) recognized as folding of previously deposited turbidite sediment sequences separated by mostly hemipelagic input during times of high sea level. Our ongoing study shows that hemipelagic rates are more than an order of magnitude less than for Santa Monica Basin., e.g., areas standing above turbidity current deposition receive 0.1 to 0.4 m/ka as opposed to 2 to 4 m/ka.

High sedimentation-accumulation rates for turbidite deposits are characteristic of the inner basins of the California Borderland during the late Quaternary. Especially for closed basins, such as Santa Barbara and Santa Monica Basins, the resulting expanded sedimentary sections can be used to date fault movements, submarine landslides, and periods of folding within the basin fill. Existing deep-tow boomer and chirp profiling technology permits high-resolution (0.5 m) imaging of the bedding and structure of turbidite deposits, including those with relatively high fraction of coarse-grained sediment. With sedimentation rates as great as 4 m/ky (Piper et al., 2003), it is possible to date depositional events to within 125+/-100 years within the upper 50 to 75 m of the basin fill (using a deep-towed boomer). The combination of extensive high-resolution reflection data and ODP drilling in Santa Monica Basin has resulted in a chronostratigraphy that provides age control for Holocene deformation and landslide events around the margins of Santa Monica Basin (this study; Fisher et al., 2003; Normark and McGann, 2003).

The main problem for developing a high-resolution chronostratigraphy in turbidite deposits is the difficulty in obtaining samples for dating that can be used to assign ages. ODP Sites 893 (Santa Barbara Basin) and 1015 are the only scientific drilling available within the inner basins of the Borderland. Giant piston cores, such as the French Calypso piston corer that was used to obtain 40-m cores in Santa Barbara Basin (Beaufort et al., 2002), are less successful in basins with high sand content and also are not commonly available for use off the western U.S. As a result, current efforts to date deformation events and landslides in the Borderland are relying on standard piston cores, which rarely exceed 5-m recovery in sand-rich sediment. Deformation histories in the Catalina Basin (in lieu of ODP style drilling) and other sandy basin-fill areas will need to be based on deep-tow boomer or chirp high-resolution profiling to select core sites from starved sections along basin slopes such that the ages can be carried laterally into the thicker and coarser sequences. This type of effort is being conducted on the inner basins of the Borderland from the San Pedro shelf to San Diego Trough.

Turbidite deposits provide many generally parallel reflecting surfaces with which to measure fault offsets and folding. Hemipelagic and pelagic sequences, in contrast, generally have far fewer internal reflectors. High and relatively uniform sediment accumulation rates of turbidites provide a good 'tape recording' for defining deformation within basin settings. Thus, closed basins with uninterrupted deposition from turbidity currents provide the most complete recording. For basins that become cut off from a source of frequent turbidity currents, the 'tape recording' of deformation becomes intermittent at best. The slower hemipelagic depositional intervals mark condensed sequences that are seen as sequence boundaries between turbidite depositional intervals, e.g., as seen in Catalina Basin.

Rapid and continuous deposition of turbidites, however, does not necessarily provide unequivocal evidence for tectonic deformation simply because of onlap at basin margins or thinning of beds over the crest of anticlinal structures. Recent research on turbidite deposits shows that recognizing subtle growth folds may be difficult because individual flows can deposit over a large vertical range, e.g., >40 m for Santa Monica Basin (Piper et al., 2003) or even as much as 400 m on large deep-water turbidite systems. Therefore, onlap of turbidites along basin margins does not require uplift of the adjacent slope. This suggests that one should not trust to tectonism that which can be fully explained by depositional processes.

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FIGURE CAPTIONS

FIGURE 01 Bathymetric map showing Catalina Island, Santa Cruz-Catalina Ridge and the adjacent basins (adapted from NOAA, 1998). Light gray lines show tracklines of seismic-reflection data used for the USGS offshore earthquake hazard study related to the topic of this report. Bold black lines show location of profiles illustrated in this study. Faults shown in red are adapted from (Greene and Kennedy, 1986 and Fisher et al., 2003, 2004).

FIGURE 02 Depth and age of key reflectors in Santa Monica Basin. (A) Schematic sediment log for ODP Site 1015 showing depth and the interpolated age of key reflectors D to O. Arrows along left side of the sediment log indicate the depth of subsamples used for radiocarbon dating the sediment (simplified from Piper et al., 2003; Normark and McGann, 2004). Estimated ages for key reflectors A to C shown as inset above legend for the sediment log. (B) Deep-tow boomer seismic-reflection profile that crosses ODP Site 1015 showing key reflectors in the upper 35 m of basin floor turbidites. Not all of the key reflectors, e.g., K, can be followed with confidence from the western end of Santa Monica Basin where they were defined. (C) Sparker seismic-reflection profile that passes close to the drill site showing the key reflectors below J. See Figure 1 for location of profiles. The velocity-amplitude (vamp) anomaly is one of several acoustic effects caused by methane hydrate recognized on reflection profiles in the southeastern end of the basin (Normark et al., 2003). (D) Sediment accumulation rate for ODP 1015 based on radiocarbon ages (adapted from Normark and McGann, 2004).

FIGURE 03 Seismic-reflection profile using sleeve-gun sound source from northwestern corner of Santa Monica Basin showing broad anticlinal feature that formed in strata below key reflector A and that exhibits several small fault offsets near the anticlinal axis. Hueneme Fan turbidite deposits onlap the northeast limb with little evidence for significant folding post reflector B. The sedimentation rate nearly doubled (Fig. 2D) in the interval from reflector F to just above J (compared to the A to F interval) allowing the fan deposits to bury the fold. Above J, the sedimentation rate is much lower (about 25% of the late Pleistocene rate) until the last few thousand years; during this interval the modern sea floor has been slightly upbowed over the crest of the anticline, suggesting uplift of the structure (but not continued folding) occurring at a slow rate. See Figure 1 for location.

FIGURE 04 Seismic-reflection profile using sleeve-gun sound source and NSRF streamer from northwestern margin of basin adjacent to the base of the Santa Cruz-Catalina Ridge. This example shows minor warping and faulting of the basin fill prior to 'J' and the structural relief is buried by about 20 kya based on extrapolation of ages between reflectors J and C. The sediment wave might have developed as a result of turbidity currents from Hueneme Canyon flowing over sea-floor relief created by faulting during the B to C interval (see Normark et al., 2002). The apparent kinking of beds below the dotted arrow is an artifact of changing course during the survey. See Figure 1 for location.

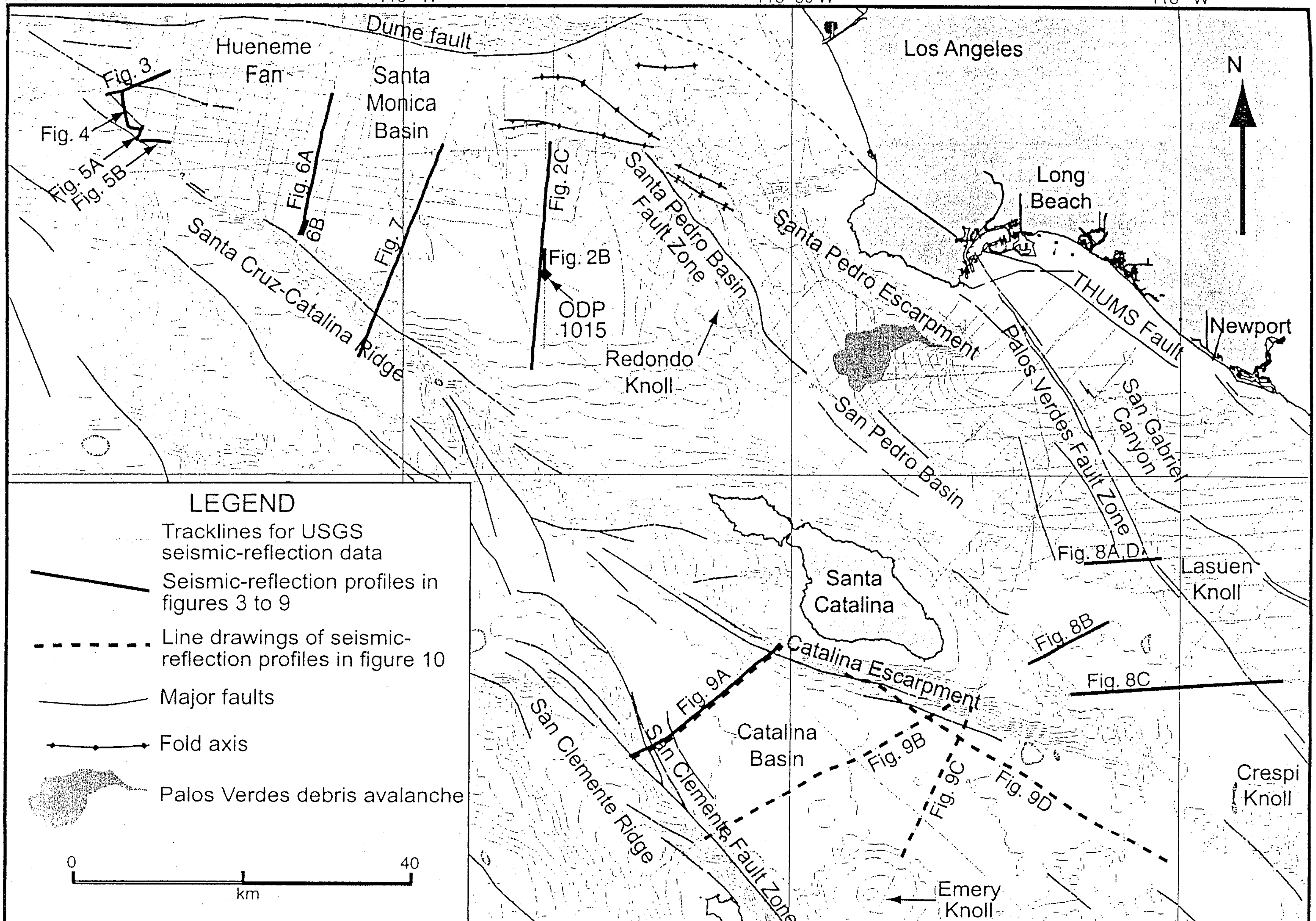
FIGURE 05 (A and B) Boomer seismic-reflection profiles at the base of Santa Cruz-Catalina Ridge (the steep slope of the ridge is poorly imaged in these profiles). Strata as young as 1.5 kya (below reflector O) have been gently folded and truncated along the edge of a small graben-like feature at the base of the slope. The hinge point lies above a fault observed in airgun profiles that shows no vertical offset after reflector F, a condition similar to that shown in Figure 4. See Figure 1 for location.

FIGURE 06 Seismic-reflection profiles normal to the margin of Santa Monica Basin about 18 km southwest of profiles shown in Figure 5. (A) Sleeve-gun profile showing turbidite strata onlapping flank of Santa Cruz-Catalina Ridge with little evidence for deformation of strata since key reflector A was deposited about 75 kya. The relief on the low anticline is about 18 m at the time of reflector A, 10 m at B, and 7 m at C as the structure is gradually buried. The possible upwarp of strata along the SC-CR ridge appears only in strata above reflector A and does not affect lower deposits, suggesting that the apparent upwarp results instead from depositional effects (dashed line shows thickness of Holocene turbidity currents). (B) High-resolution deep-tow boomer profile showing little evidence for deformation during the last 3 ka (post N) and the development of a small leveed channel at the base of the ridge. The apparent upwarp seen along the base of the ridge is less than 5 m (note vertical exaggeration is 18.5 times) and can easily result as deposition from turbidity currents that are more than 40 m thick on the basin floor (i.e., all of the 'water' area in Fig. 6B is within the thickness of the turbidity currents; see 6A). See Figure 1 for location.

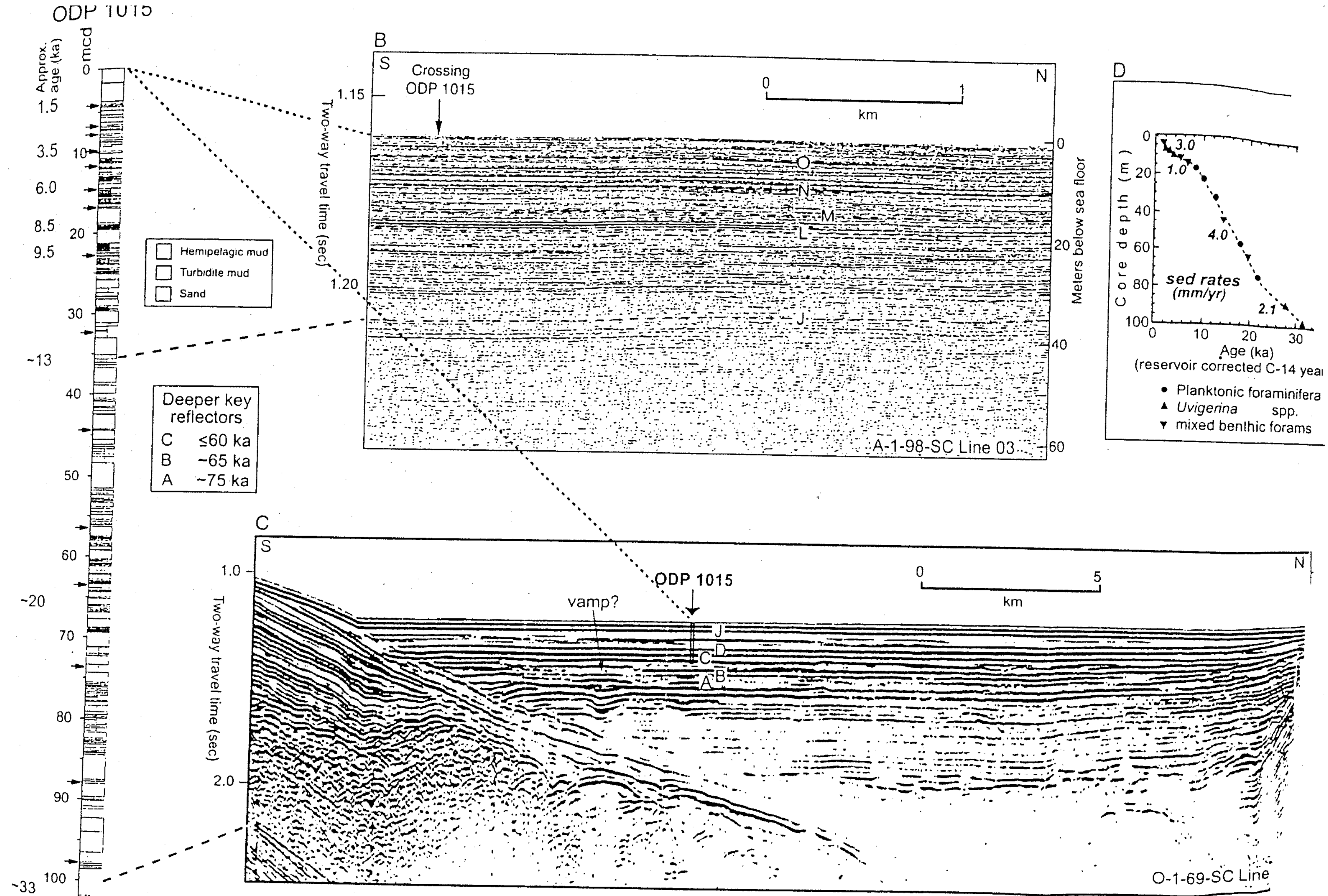
FIGURE 07 Seismic-reflection profile using sparker sound source near the southern margin of Santa Catalina Basin showing gentle warping within the nearly flat basin fill sediment younger than ~60 ky (reflector 'C'). Low relief of sediment below reflector C is compensated (eliminated) in the overlying sequence. A channel (?) along the base of the ridge that is most pronounced around the time of reflector A, might have developed along the trend of earlier faulting. On the flank of Santa Cruz-Catalina Ridge, a re-entrant on the upper slope corresponds to the position of a fault shown in Greene and Kennedy (1986; shown in our Fig. 1). This feature might mark the site of any recent movement in the time frame of deformation observed in the boomer profiles of Figure 5. See Figure 1 for location.

FIGURE 08 Shaded-relief image (upper left) and seismic-reflection profiles (A to D) showing the channel from San Gabriel Canyon where it crosses San Pedro Basin. The small arrows in upper part of the shaded-relief image indicate the present position of the coastline, which is well inboard from the head of San Gabriel Canyon. The channel has been erosionally deepened resulting in pronounced terraces observed in all crossings before entering Catalina Basin. At the northern end of Lasuen Knoll, the channel bifurcates where it crosses the Palos Verdes Fault Zone and a slump has partially blocked the eastern branch of the channel (see Figure 8 in Fisher et al., 2004a). The profiles in 8A and 8C are high-resolution multichannel profiles obtained with a 24 channel, 250-m-long streamer. Arrow at left side of A is the site of piston core used to determine sedimentation rate (see text). The profile in 8B is a single-channel record. Profile 8D is a deep-tow boomer record taken on the same line as in 8A. Note the high vertical exaggeration needed to show the thickness of the Holocene deposits. See Figure 1 for location of illustrated profiles. Shaded relief image courtesy of P. Dartnell.

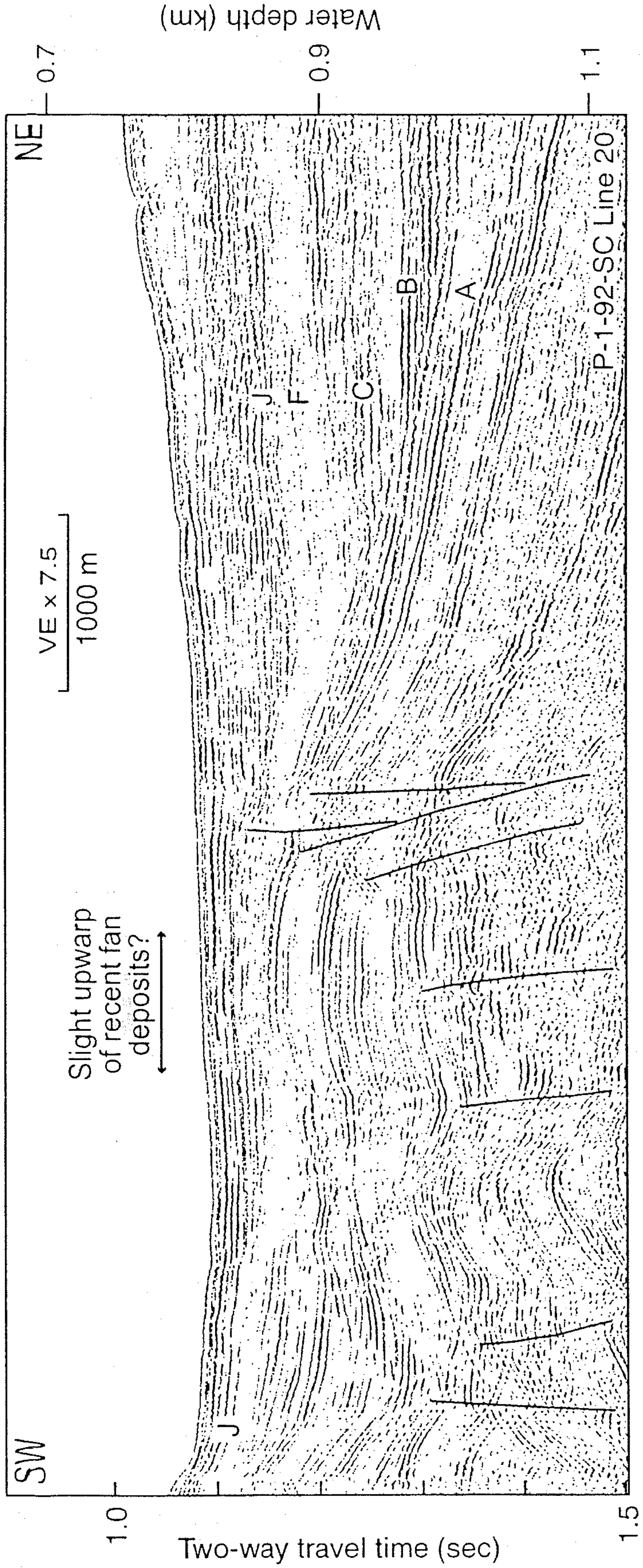
FIGURE 09 Seismic-reflection profiles from Catalina Basin. Profiles in A, B, and D are single-channel records using a high-resolution streamer with a tuned airgun array source for multichannel profiling. The profile is C is from one channel of the LARSE-1 multichannel streamer; the lower frequency content of this untuned airgun array results in even lower resolution of the sediment fill in the basin. See Figure 1 for location. The line-drawing interpretation delineates sedimentation units that can be roughly correlated among the four profiles.



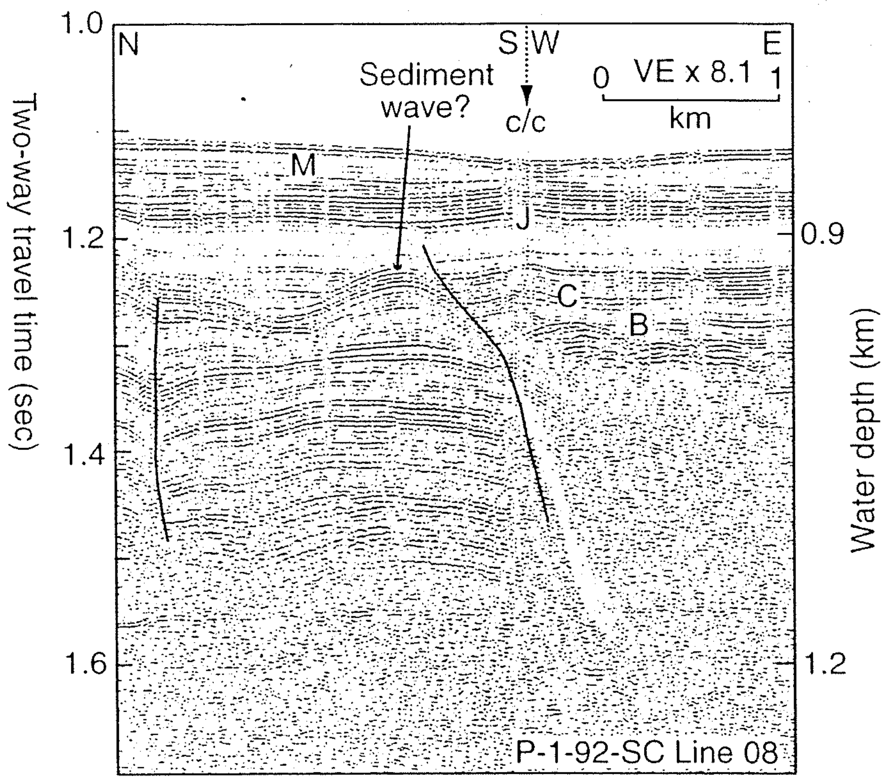
Normark et al. Fig. 01


ODP 1015
Approx. age (ka)
omcd
Hemipelagic mud
Turbidite mud
Sand
Deeper key reflectors
C ≤60 ka
B ~65 ka
A ~75 ka
B
S
N
Crossing ODP 1015
Two-way travel time (sec)
Meters below sea floor
km
A-1-98-SC Line 03
D
Core depth (m)
sed rates (mm/yr)
Age (ka)
(reservoir corrected C-14 yea
Planktonic foraminifera
Uvigerina spp.
mixed benthic forams
C
ODP 1015
vamp?
O-1-69-SC Line

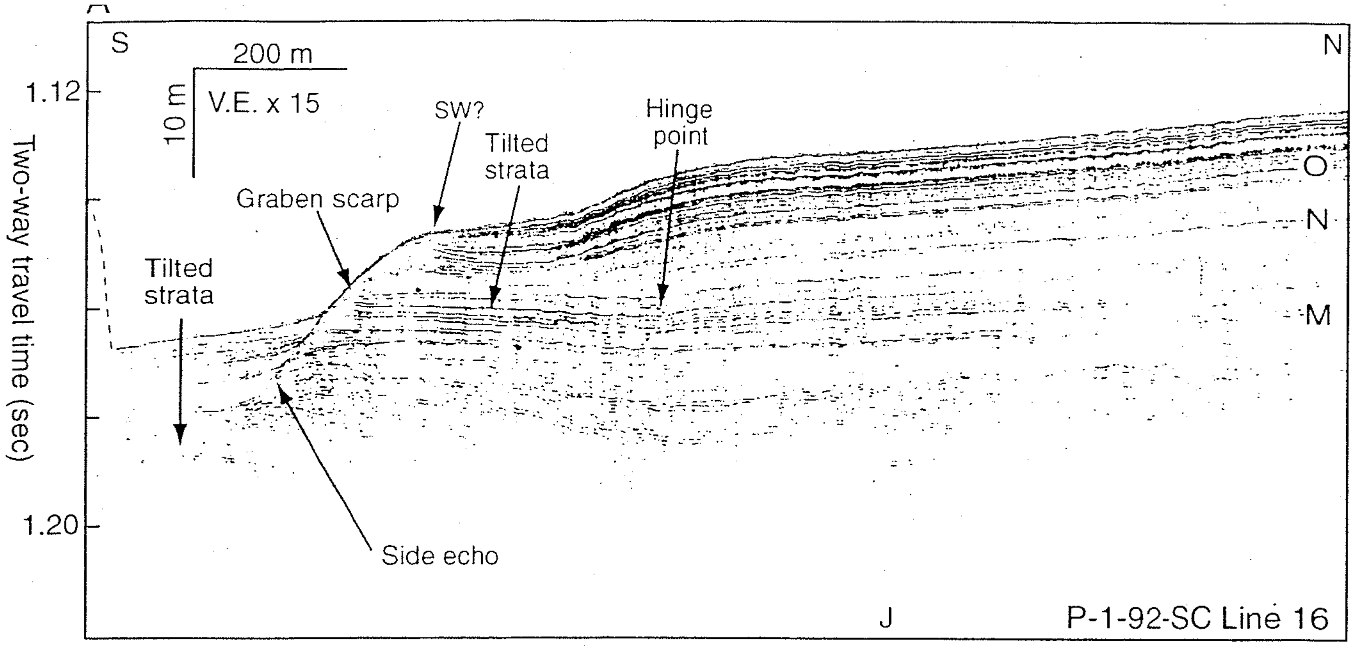
Normark e

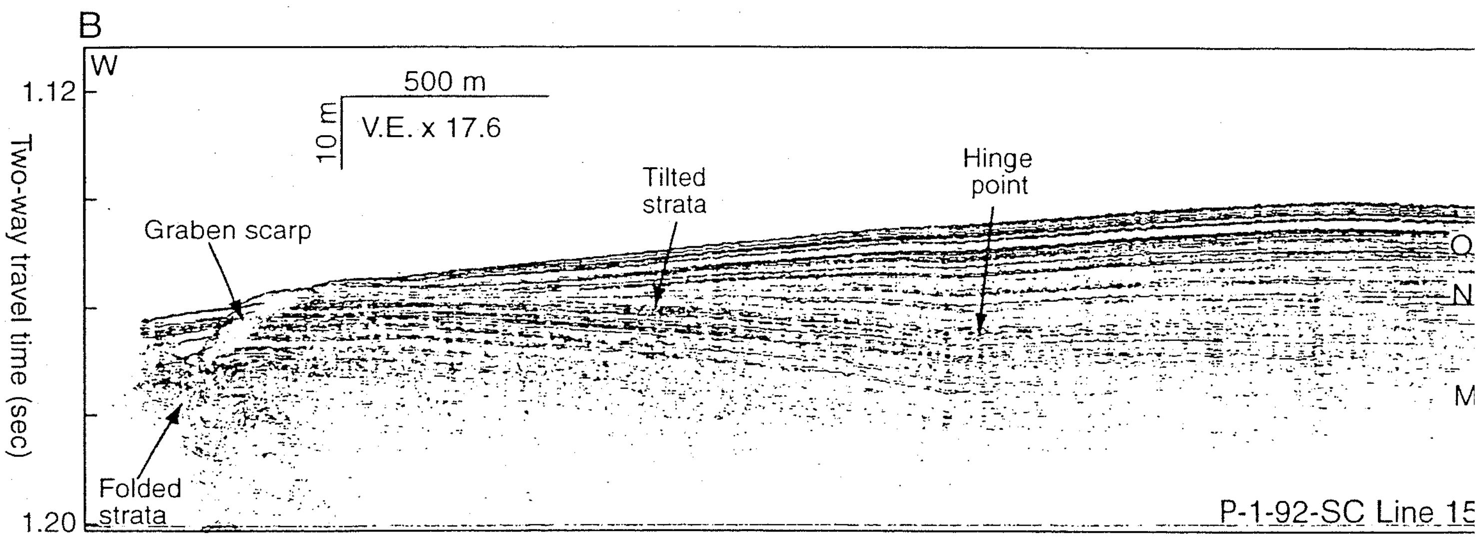


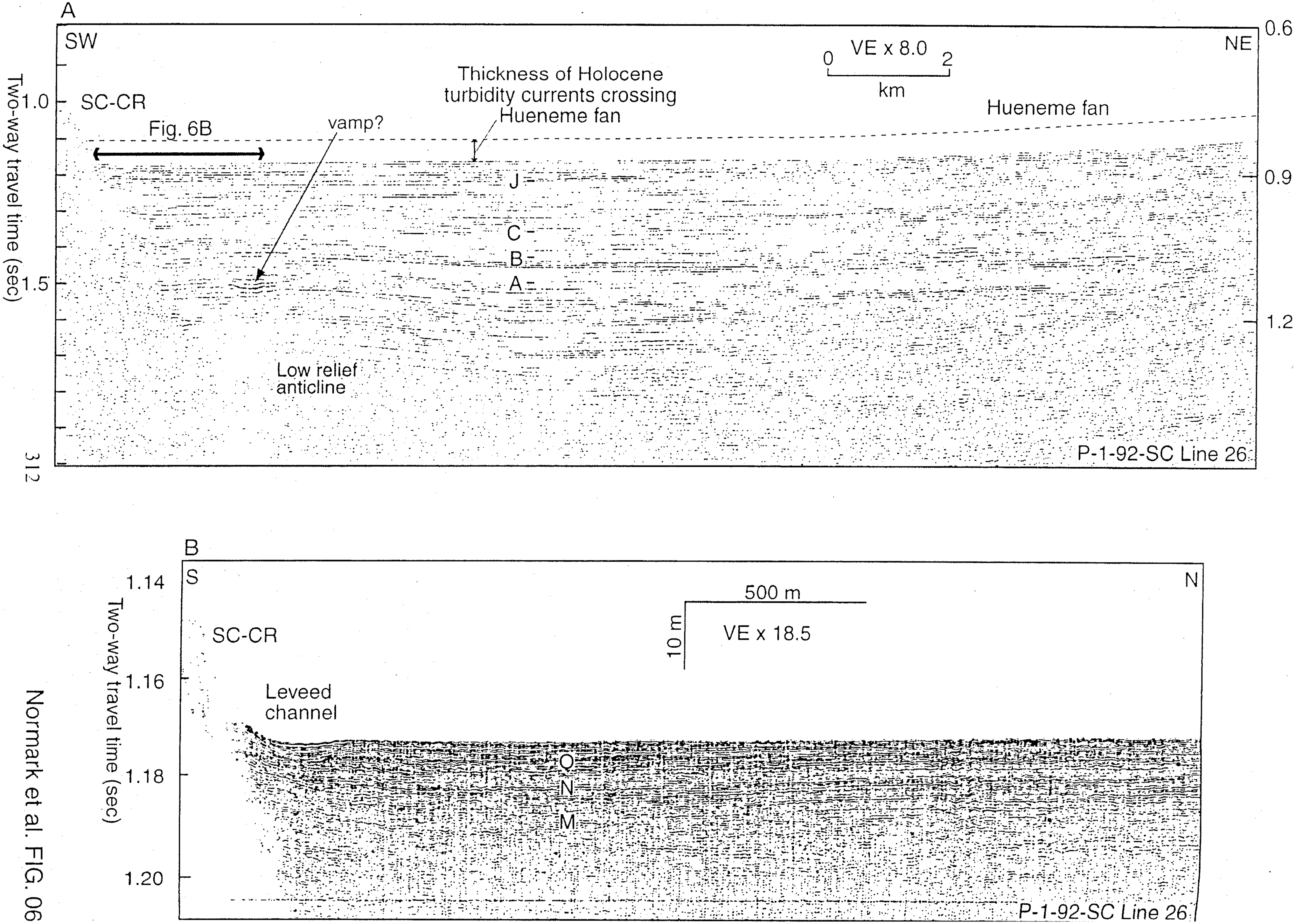
Normark et al. FIG. 03



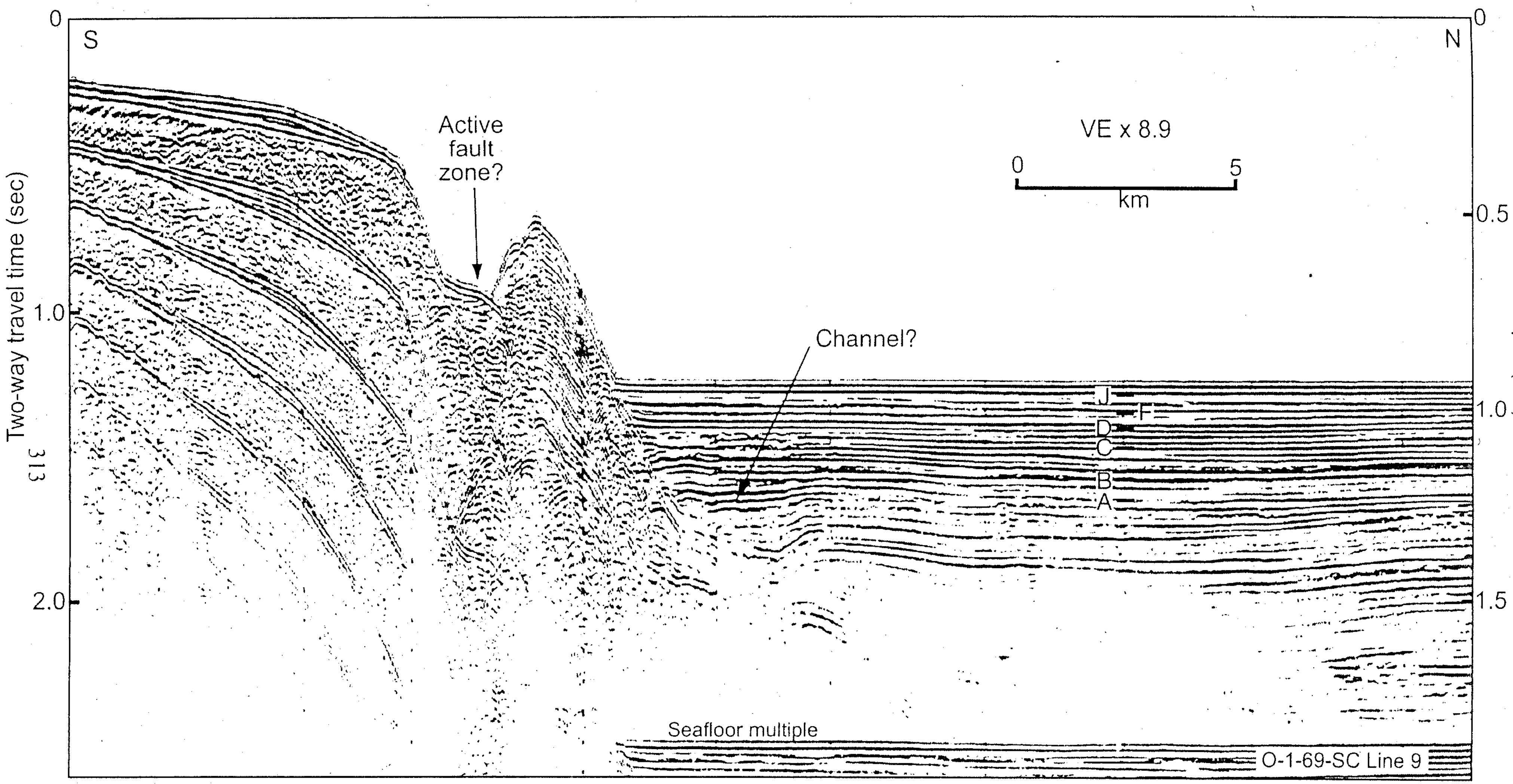
Normark et al. FIG 0·


A
S
N
200 m
10 m
V.E. x 15
1.12
1.20
Two-way travel time (sec)
SW?
Tilted strata
Hinge point
Graben scarp
Tilted strata
O
N
M
Side echo
J
P-1-92-SC Line 16

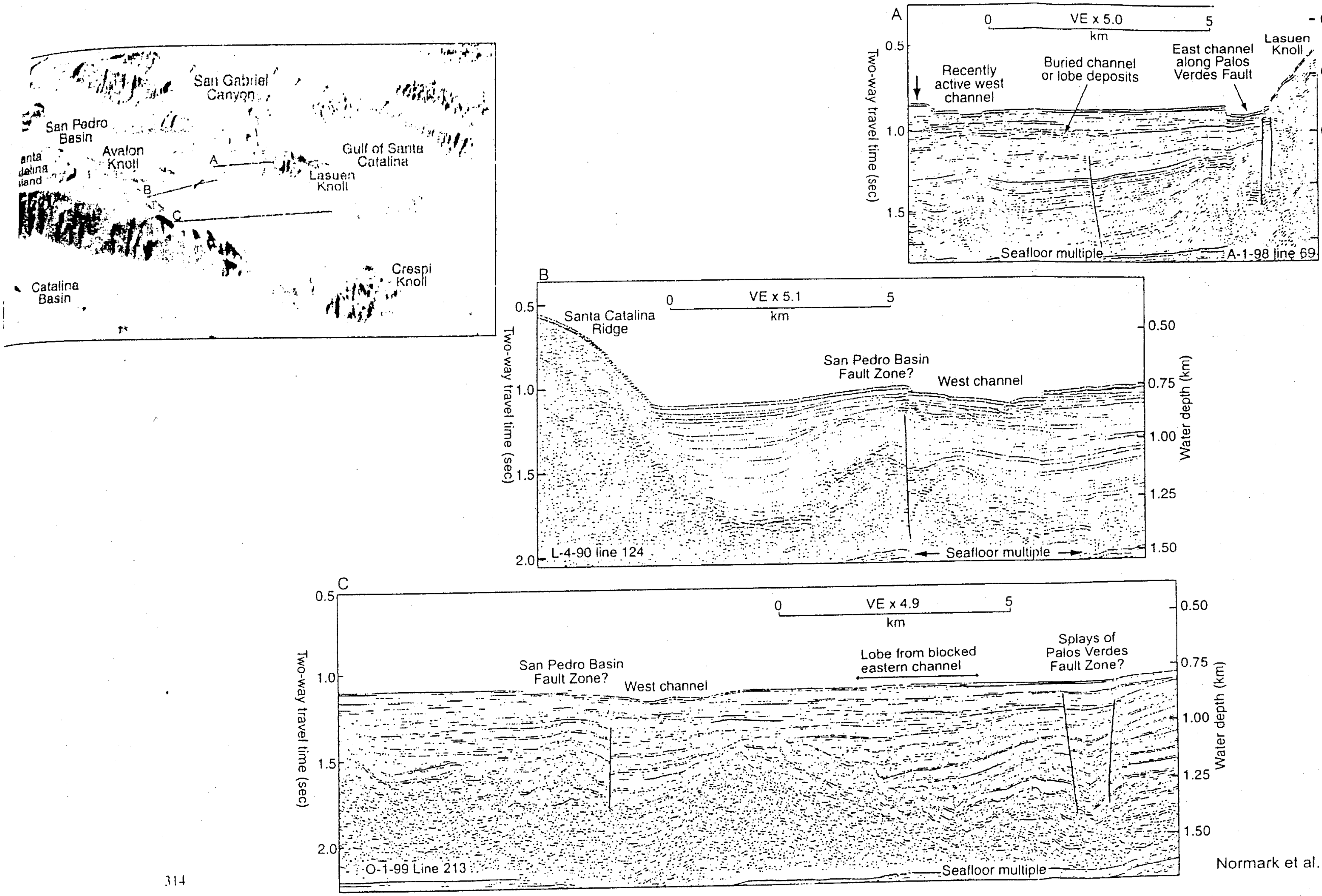

B
W
1.12
1.20
500 m
10 m
V.E. x 17.6
Two-way travel time (sec)
Tilted strata
Hinge point
Graben scarp
O
N
M
Folded strata
P-1-92-SC Line 15



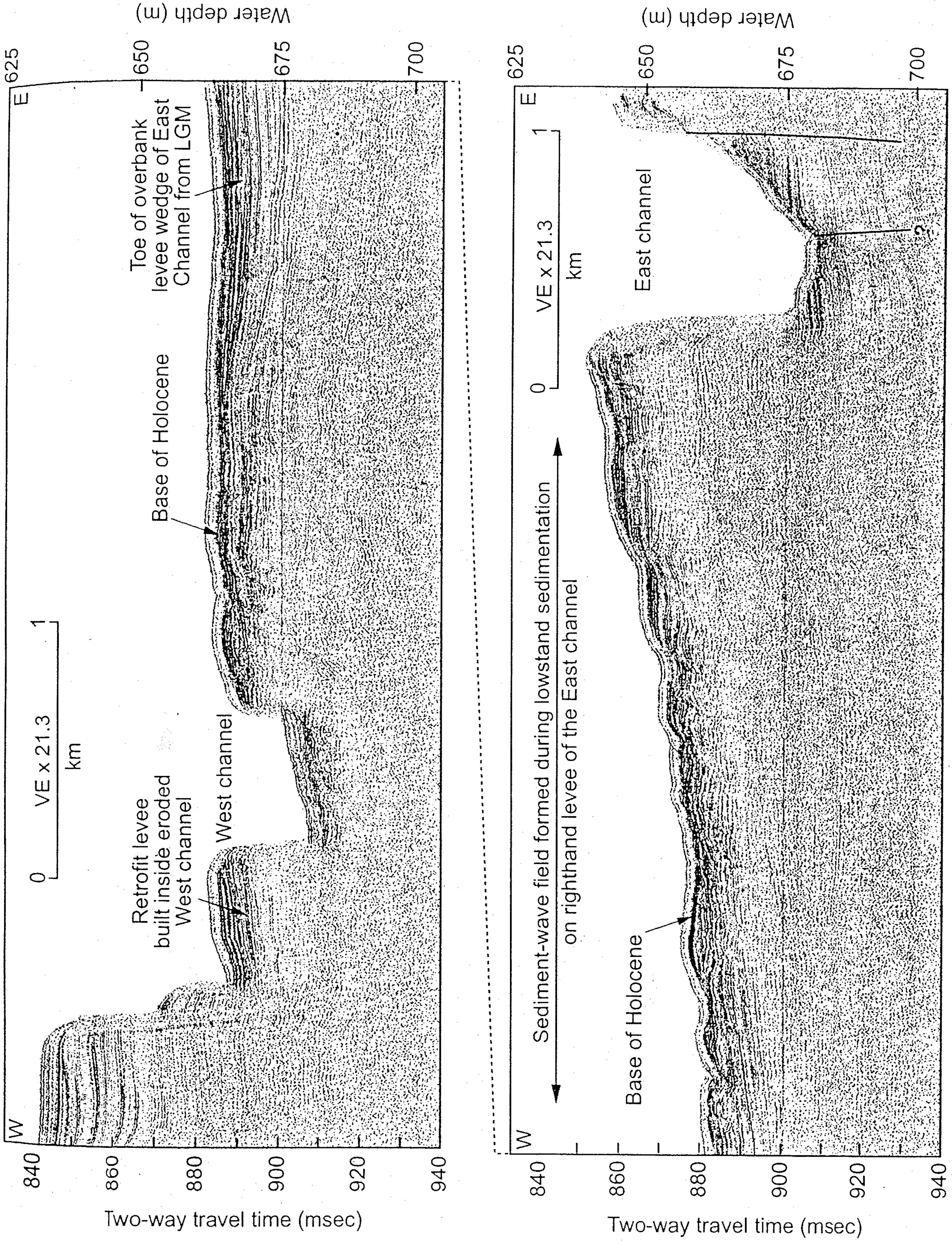
Normark et al. FIG. 06



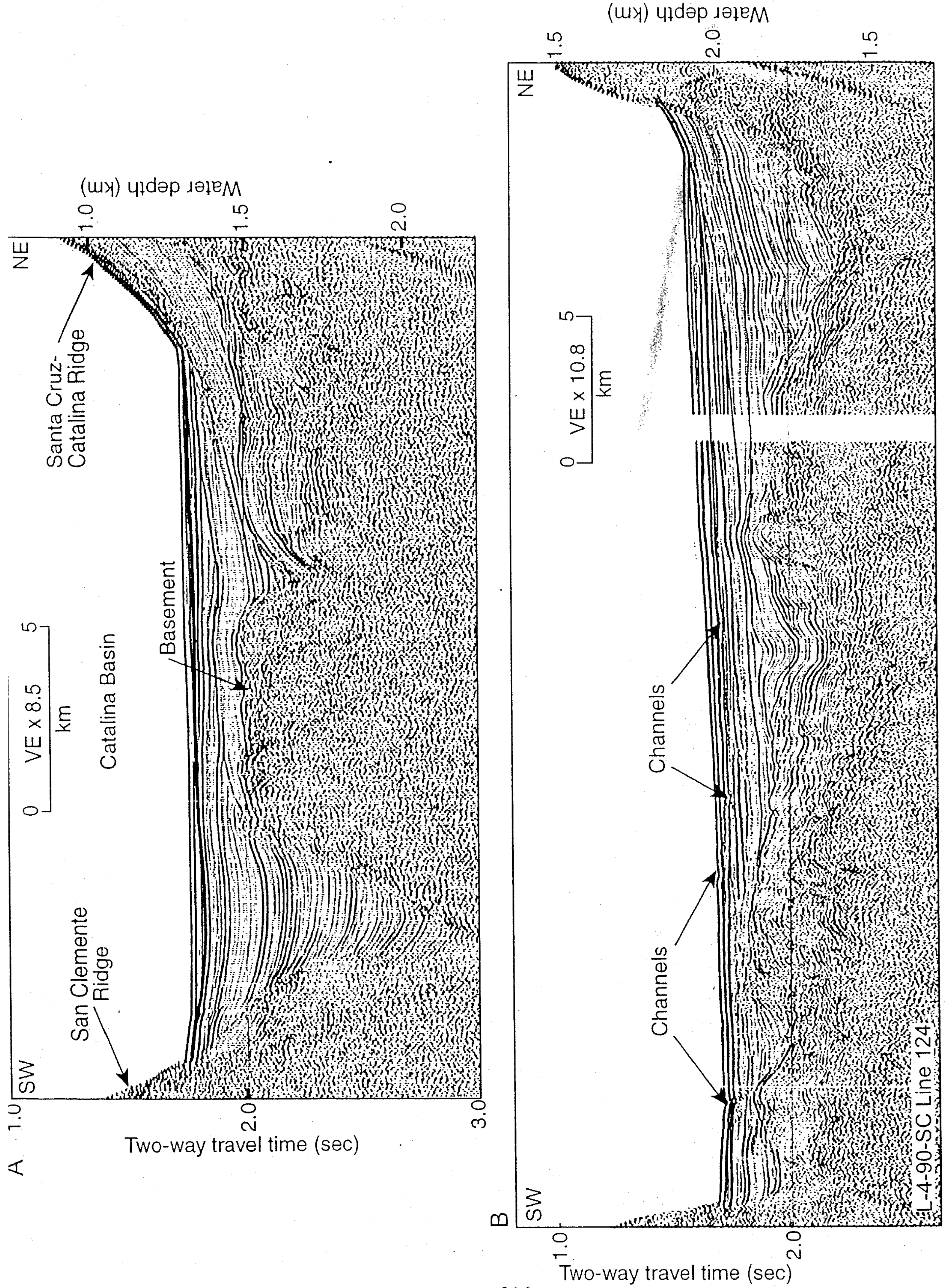
Normark et al. FIG 07



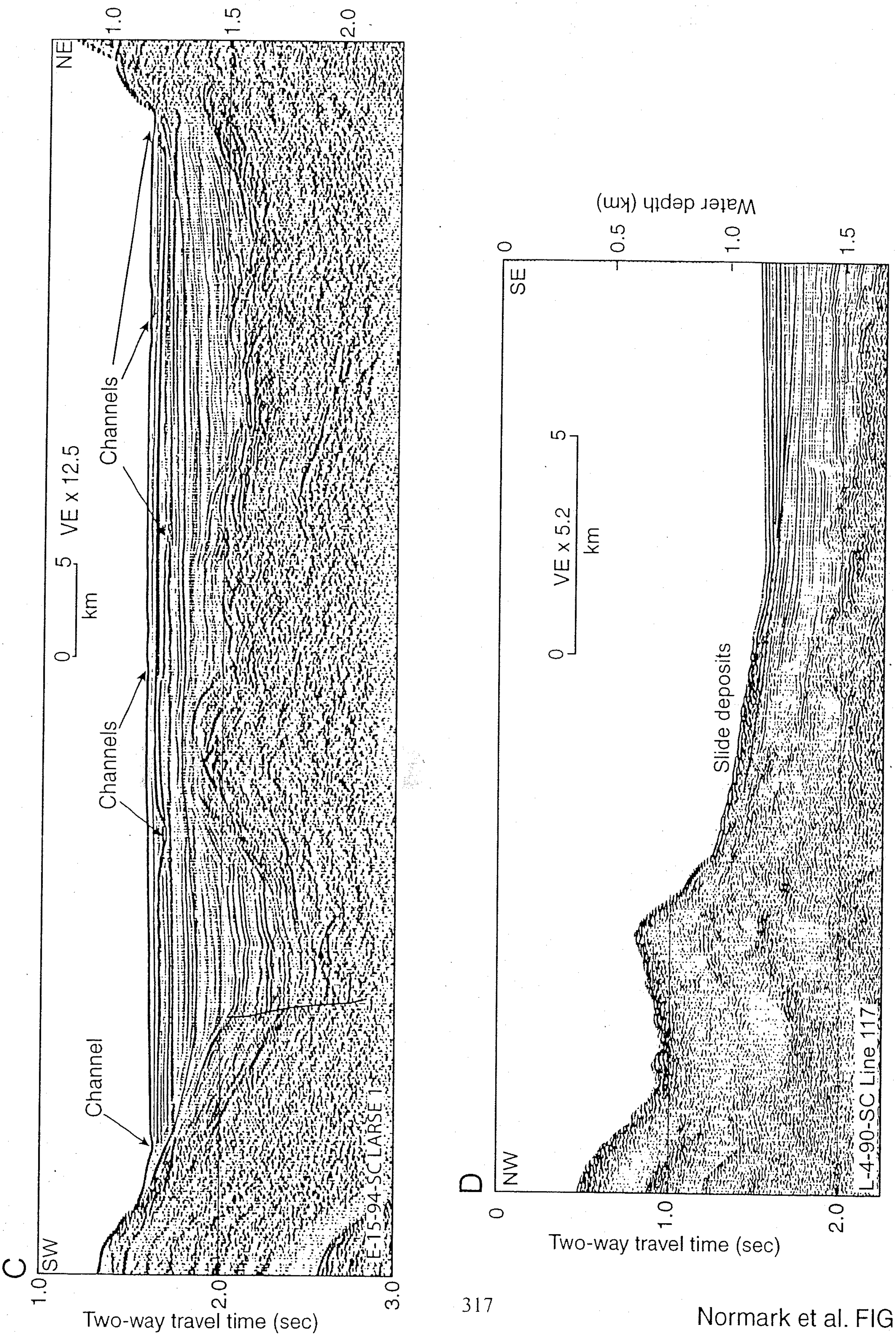
Normark et al. FIG.



Normark et al. FIG. 8I



Normark et al., FIG 09A,B



Normark et al. FIG 09C,D

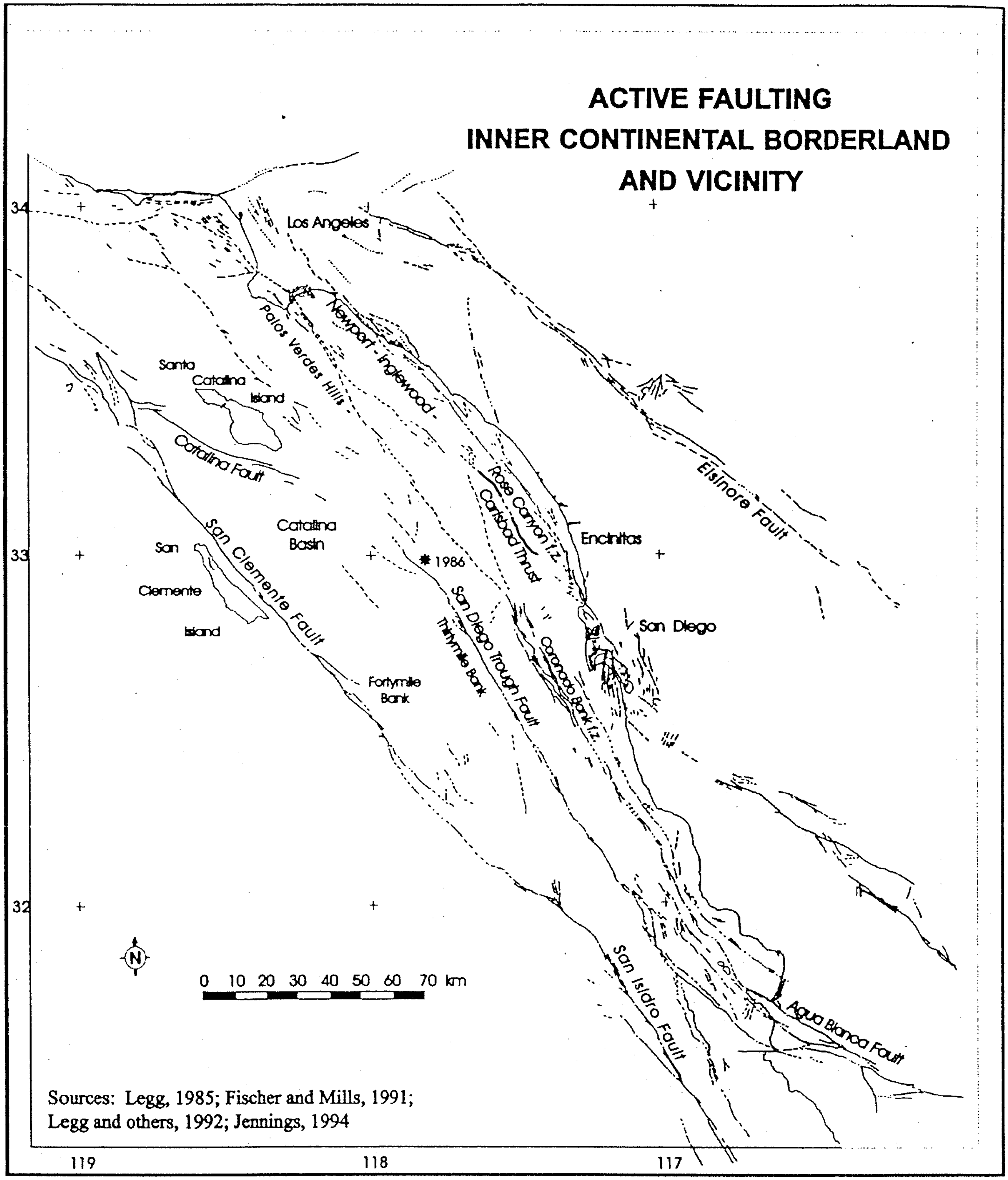


Figure 1. Map of the offshore Inner Borderland, which is bounded on the west by the San Clemente fault and on the north by the Western Transverse Ranges (34° N latitude).